

## PROGRESS IN THE DEVELOPMENT OF METAMORPHIC MULTI-JUNCTION III-V SPACE-SOLAR CELLS AT ESSENTIAL RESEARCH INCORPORATED<sup>1</sup>

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### Abstract

Theoretical calculations have shown that highest efficiency III-V multi-junction solar cells require alloy structures that cannot be grown on a lattice-matched substrate. Ever since the first demonstration [1] of high efficiency metamorphic single junction 1.1 eV and 1.2 eV InGaAs solar cells by Essential Research Incorporated (ERI), interest has grown in the development of multi-junction cells of this type using graded buffer layer technology. ERI is currently developing a dual-junction 1.6 eV InGaP/1.1 eV InGaAs tandem cell (projected practical air-mass zero (AM0), one-sun efficiency of 28%, and 100-sun efficiency of 37.5%) under a Ballistic Missile Defense Command (BMDO) SBIR Phase II program. A second ongoing research effort at ERI involves the development of a 2.1 eV AlGaInP/1.6 eV InGaAsP/1.2 eV InGaAs triple-junction concentrator tandem cell (projected practical AM0 efficiency of 36.5% under 100 suns) under a SBIR Phase II program funded by the Air Force. We are in the process of optimizing the dual-junction cell performance. In case of the triple-junction cell, we have developed the bottom and the middle cell, and are in the process of developing the layer structures needed for the top cell. A progress report is presented in this paper.

### Introduction

Multi-junction tandem space solar cells currently in production consist of an InGaP top cell and a GaAs bottom cell for the dual-junction cell, and an InGaP top cell, GaAs middle cell, and Ge bottom cell in case of the triple-junction cell. The top two cells are lattice-matched, whereas GaAs and Ge are nearly lattice-matched to each other. Typical AM0, one-sun efficiencies of these production cells are 23% for the dual-junction cell, and 25 – 26% for the triple-junction cell. Further optimization of these lattice-matched cells is not expected to yield significant improvement in the efficiency values. Theoretical calculations [2] for the dual-junction configuration have shown that significant enhancement in the upper limit efficiency can be achieved only if the constraint of lattice-matched growth is relaxed. The approach taken by ERI towards the realization of very high efficiency space solar cells is to develop a proprietary, step-graded buffer layer scheme that allows the growth of very low defect density, lattice-mismatched InGaAs on GaAs and InP substrates. The validity of this approach was demonstrated for the first time when ERI researchers announced [1] the fabrication of high efficiency, metamorphic, single-junction 1.1 eV and 1.2 eV InGaAs solar cells on GaAs substrates using their buffer layer scheme. Following that first success, ERI [3 – 5] and other laboratories [6, 7] have demonstrated other metamorphic single-junction cells, as well as multi-junction tandem cells using variations of this buffer layer scheme.

ERI is currently developing a dual-junction 1.62 eV InGaP/1.1 eV InGaAs concentrator tandem cell (projected practical AM0, 100-sun efficiency of 37.5%) under a Ballistic Missile Defense Command (BMDO) SBIR Phase II program. A second ongoing research effort at ERI involves the development of a 2.1 eV AlGaInP/1.6 eV InGaAsP/1.2 eV InGaAs triple-junction concentrator tandem cell (projected practical AM0 efficiency of 36.5%

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under 100 suns) under a SBIR Phase II program funded by the Air Force. In both cases, the tandem cells are lattice-matched to each other, as shown in Figure 1. The bottom InGaAs cell structure is lattice-mismatched to the GaAs substrate, and is grown using a proprietary, graded buffer layer that confines most of the misfit and threading dislocations to the substrate-buffer interface [3], resulting in very low defect density active cell regions. Results of modeling calculations of theoretical and practical AM0, one-sun efficiencies of the two tandem cells under development are shown in Table 1. Modeled experimental efficiencies of these cells are significantly higher than currently available commercial dual- and triple-junction cells. Progress in the development of the two tandem cells is described in the following sections.

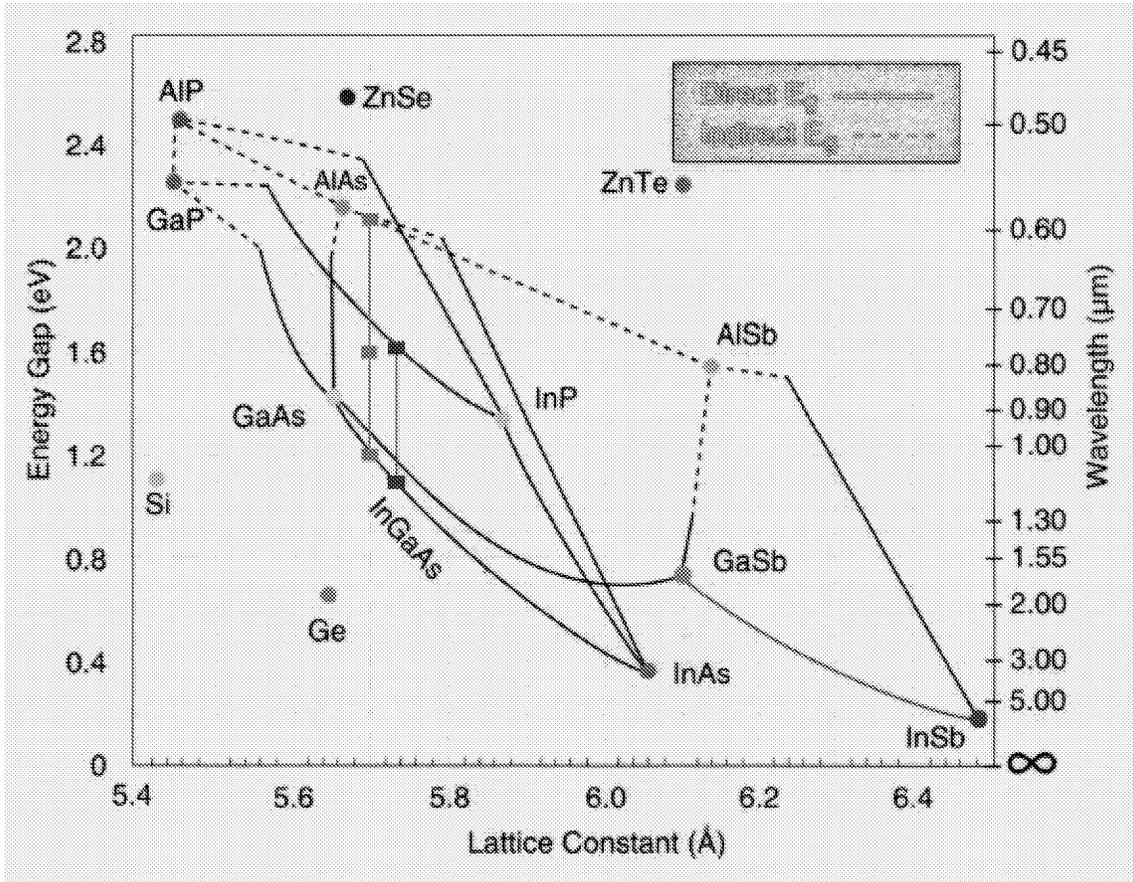


Figure 1.— Common semiconductor bandgap vs. lattice constant chart showing the designs of the metamorphic dual-junction InGaP/InGaAs and triple-junction AlGaInP/InGaAsP/InGaAs cells under development at ERI. The component cells are connected by a vertical line in each case in the Figure.

Table I—Modeled efficiencies of the proposed dual- and triple-junction cells.

Cell Structure	Cell Bandgap (eV)			Expected AM0, One-Sun Efficiency (%)	
	Top	Middle	Bottom	Theoretical	Practical
InGaP/InGaAs	1.62	None	1.1	32.5	28
InGaAlP/InGaAsP/InGaAs	2.1	1.6	1.2	37.9	31.5

## Device Fabrication

All epitaxial layer structures for the cells were grown at NASA Glenn Research Center (GRC) using low pressure metal organic vapor phase epitaxy (LP-MOVPE) in a horizontal reactor, as described in previous publications.[3,5] The layer structures were characterized at GRC using X-ray, Hall effect measurement, and electrochemical capacitance-voltage (ECV) profiling. Transmission electron microscopy (TEM) and secondary ion mass spectroscopy (SIMS) analysis were performed by external commercial laboratories. The cells were processed at ERI facilities using standard photolithographic techniques. AM0 conversion efficiencies were measured at 25 °C using a single source, Spectrolab X25 solar simulator at GRC. Spectral response measurements were performed at GRC to determine the external quantum efficiency (EQE) of the cells. Figure 2 shows the current design of our dual-junction and triple-junction cells. In the case of the triple-junction cell, we have started by fabricating and evaluating stand-alone InGaAs and InGaAsP cells prior to combining them in a tandem cell using an appropriate tunnel junction. The results shown here will be for these two stand-alone cells. We are currently evaluating the AlGaInP top cell layer structure, and no cells have been fabricated with that material yet.

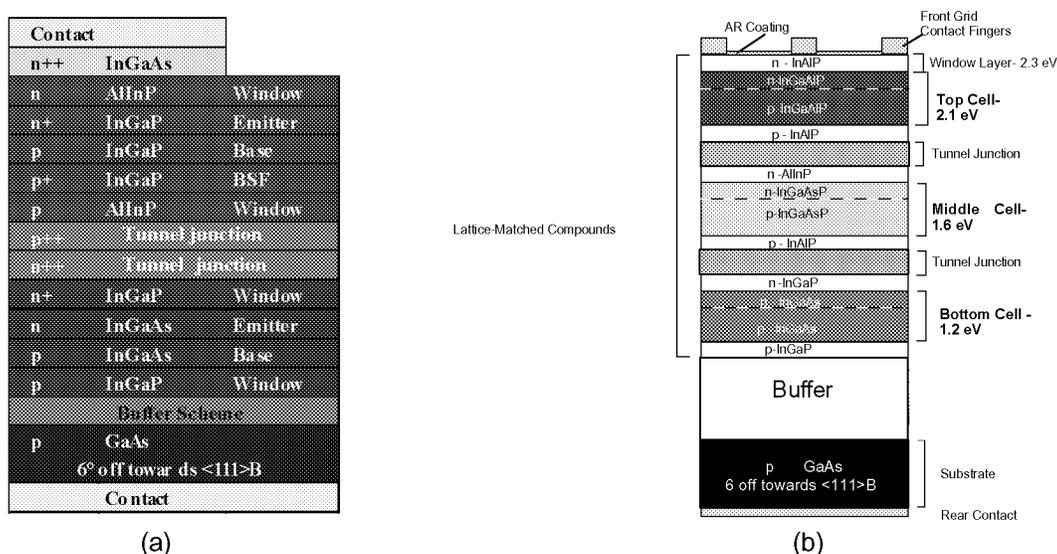


Figure 2.—Dual-junction (a) and triple-junction (b) cell structures.

## Results and Discussion

It should be noted prior to discussion of the results that none of the cells discussed in this paper has been coated with anti-reflection (AR) coating. Shown in Figure 3 is the light current-voltage characteristic of a 1.62 eV/1.1 eV n/p dual-junction cell. The cell is characterized by open circuit voltage ( $V_{oc}$ ) = 1864 mV, short circuit current ( $J_{sc}$ ) = 15.605 mA, fill factor (FF) of 83.4%, and an AM0, one-sun efficiency of 17.76%. With an appropriate AR coating, this efficiency should increase to 24.8%. This is a significant improvement over our previously reported [5] result of 19%, and can be attributed to switching the tunnel junction material from 1.1 eV InGaAs to a wider bandgap material, as well as thinning of the top cell. The external quantum efficiency (EQE) of the subcells of the dual-junction cell was measured using appropriate filters, and the results are shown in Figure 4. Analysis of the I-V and EQE data and comparison with computer modeled data shows that the performance of the dual-junction cell is being controlled by the bottom cell, in spite of the top cell thinning so far to achieve current matching conditions. Further optimization experiments are currently underway, and we expect to achieve the predicted practical efficiency of 28% in the near future.

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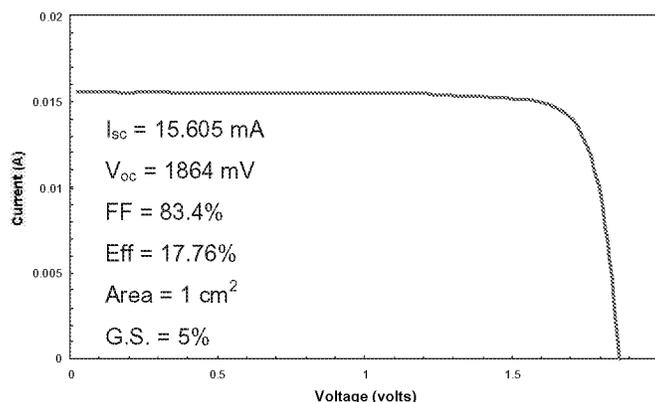


Figure 3.—I-V characteristic of dual-junction cell. Expected AM0, one-sun efficiency with appropriate AR coating = 24.8%

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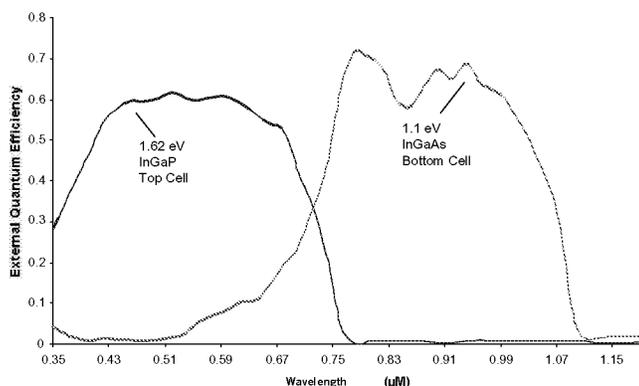


Figure 4.—External quantum efficiency of dual-junction cell.

In case of the triple-junction cell shown in Figure 2(b), we have started by fabricating and testing the component individual cells first, prior to putting them in tandem configuration. The 1.2 eV InGaAs bottom cell, and the 1.6 eV InGaAsP middle cell structures were grown on GaAs substrates using an appropriate buffer layer structure. In case of the 1.6 eV cell, the structure was similar to that shown in fig. 2(b), except that we used 1.7 eV InGaP instead of wider bandgap AlInP as the window layers for initial testing purposes. Both cells were capped with a thin InGaAs layer.

Current-voltage and external quantum efficiency characteristics of the 1.2 eV InGaAs cell are shown in Figure 5. The measured efficiency under AM0, one-sun condition was 11.73% without AR coating. With an appropriate AR coating, this efficiency should increase to 16.4%. The high efficiency value compares well with similar cells fabricated by ERI in the past. However, as can be seen from the EQE data of Figure 5, it should be possible to improve the efficiency even further by increasing the absorption in the blue region through improvements in the window material.

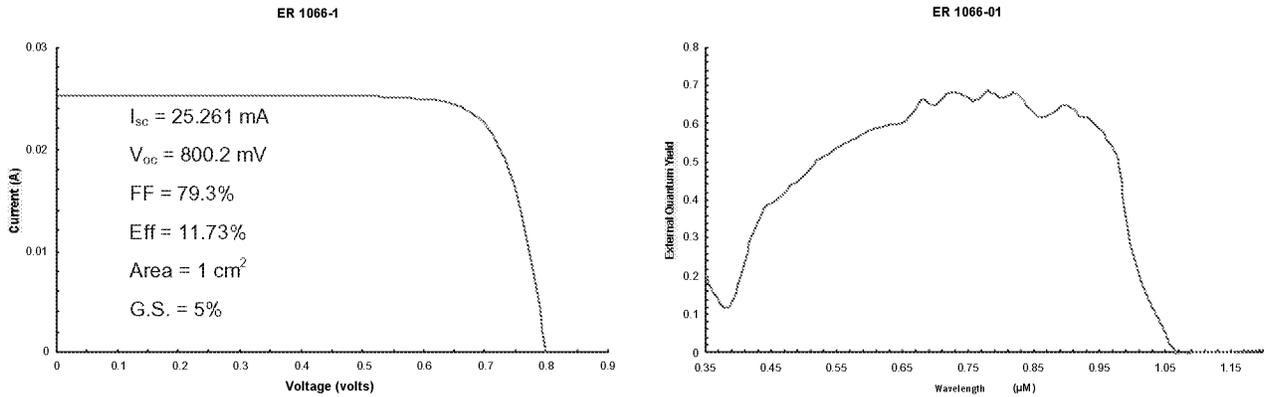


Figure 5.—*I-V and EQE characteristics of 1.2 eV InGaAs cell. AM0, one-sun efficiency of this cell with appropriate AR coating is expected to be 16.4%.*

Current-voltage and external quantum efficiency characteristics of the 1.6 eV InGaAsP cell are shown in Figure 6. The measured efficiency under AM0, one-sun condition was 8.99% without AR coating. With an appropriate AR coating, the efficiency should increase to 12.4%. Since this is the very first metamorphic 1.6 eV InGaAsP cell, there is no prior cell to compare it with. However, the drop off in the blue response in the EQE data indicates that significant loss in blue light conversion occurred due to absorption in the InGaP window. Replacing the InGaP window with 2.3 eV AlInP window should correct this problem and increase efficiency further.

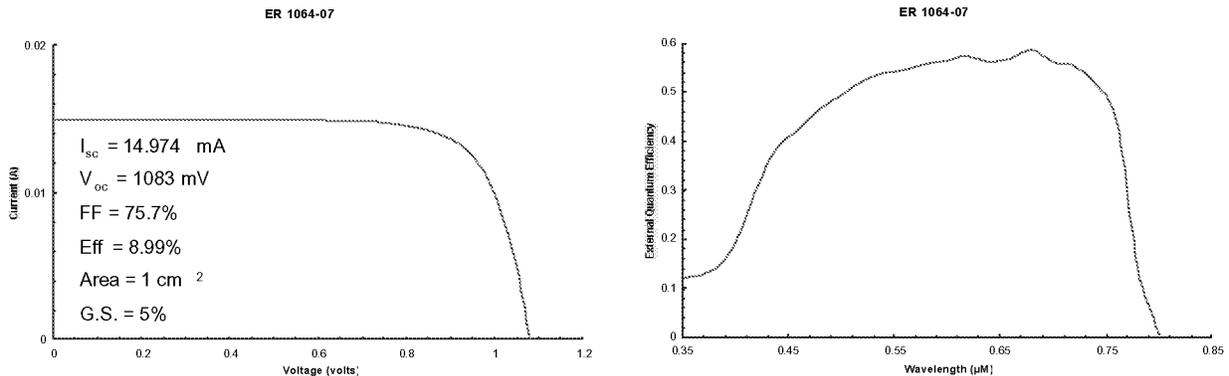


Figure 6.—*I-V and EQE characteristics of 1.6 eV InGaAsP cell. AM0, one-sun efficiency of this cell is expected to increase to 12.4% with an appropriate AR coating.*

The next step in the development of the triple-junction cell is the fabrication and testing of a 2.1 eV AlGaInP top cell, as well as combining the 1.2 eV InGaAs bottom cell and the 1.6 eV InGaAsP middle cell into a dual-junction tandem cell for evaluation. We have grown epitaxial AlGaInP layers on GaAs using our graded buffer layer. Triple-axis X-ray reciprocal lattice map analysis coupled with photoluminescence measurements indicate that the material is of high crystalline quality, and has the expected lattice constant and bandgap. We are in the process of performing p- and n-doping calibration experiments of this material prior to growing a cell structure. The tunnel junction between the bottom and the middle cell will be similar to that used in the dual-junction cell. The tunnel junction between the middle and the top cell will have to be a wider bandgap material. One of the candidate materials is AlGaInP. We plan to evaluate degenerate n- and p-doping characteristics of this material in the near future prior to fabricating a triple-junction cell.

## Summary

In summary, we have demonstrated ~25% AM0, one-sun efficiency in a 1.6 eV/1.1 eV InGaP/InGaAs metamorphic dual-junction tandem cell on a GaAs substrate using a proprietary step-graded buffer layer. External quantum efficiency measurements showed that the dual-junction cell performance was bottom cell current limited. We expect to achieve the predicted practical efficiency of 28% in the very near future through further optimization of the cell structure. Our approach to the development of a triple-junction metamorphic 2.1 eV AlGaInP/1.6 eV InGaAsP/1.2 eV InGaAs cell on GaAs has been to fabricate and evaluate the individual cells on GaAs first, prior to combining them in the tandem configuration. So far, we have demonstrated the InGaAs bottom cell and InGaAsP middle cell with AM0, one-sun efficiencies of 16.4% and 12.4% respectively. The efficiency of the InGaAsP cell is expected to improve substantially once the window material is changed from 1.7 eV InGaP to 2.3 eV InAlP in this cell. Development of the AlInGaP top cell and the tunnel junction structures are in progress.

## References

- [1] Richard W. Hoffman, Jr., Navid S. Fatemi, Mark A. Stan, Philip Jenkins, Victor G. Weizer, David A. Scheiman, and David J. Brinker, "High Efficiency InGaAs-on-GaAs Devices for Monolithic Multi-junction Solar Cell Applications", Proc. 2<sup>nd</sup> World Conf. Photovoltaic Solar Energy Conversion, pp3604-3608, Vienna, Austria, 6 – 10 July, 1998.
- [2] J. C. C. Fan, B-Y. Tsauro, and B. J. Palm, "Optimal Design of High Efficiency Tandem Cells", Proc. 16<sup>th</sup> IEEE Photovoltaic Specialists Conf., p692 (1982).
- [3] R. W. Hoffman, Jr., N. S. Fatemi, M. A. Stan, P. Jenkins, V. G. Weizer, D. A. Scheiman, and D. J. Brinker, "High Efficiency Monolithic Multi-junction Solar Cells using Lattice-Mismatched Growth", Materials Research Society Symp. Proc. 551, 51 (1999).
- [4] Mark A. Stan, Victor G. Weizer, AnnaMaria Pal, Linda M. Garverick, Osman Khan, Samar Sinharoy, Richard W. Hoffman, Philip P. Jenkins, David A. Scheiman, and Navid S. Fatemi, "High Efficiency Multi-junction Space Solar Development Utilizing Lattice Grading", 16<sup>th</sup> Space Photovoltaic Research and Technology Conf. (SPRAT), pp122 – 128, Cleveland, OH, Aug. 31 to Sept. 2, 1999.
- [5] Samar Sinharoy, Mark A. Smith, Victor G. Weizer, AnnaMaria Pal, Osman Khan, David A. Scheiman, and Philip P. Jenkins, "1.62 eV/1.1 eV InGaP/InGaAs Dual-junction Solar Cell Development on Lattice-mismatched GaAs", Proc. 28<sup>th</sup> IEEE Photovoltaic Specialists Conf. (PVSC), pp1285 – 1288, Anchorage, AK, 15 – 22 Sept. 2000.
- [6] Frank Dimroth, Peter Lanyi, Mathias Meusel, Ute Schubert, and Andreas W. Bett, "New Lattice-mismatched GaInP/GaInAs Tandem Solar Cell Concepts for High Efficiency Space and Terrestrial Concentrator Solar Cells", Proc. 16<sup>th</sup> European Photovoltaic Solar energy Conf. Glasgow, UK 1 – 5 May, 2000.
- [7] R. R. King, M. Haddad, T. Isshiki, P. Colter, J. Ermer, H. Yoon, D. E. Joslin, and N. H. Karam, "Metamorphic GaInP/GaInAs/Ge Solar Cells", Proc. 28<sup>th</sup> IEEE PVSC, pp982 – 985, Anchorage, AK, 15 – 22 Sept. 2000.